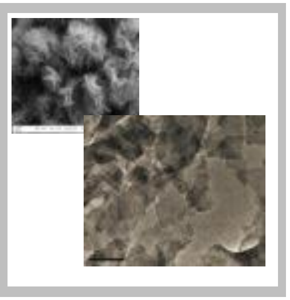

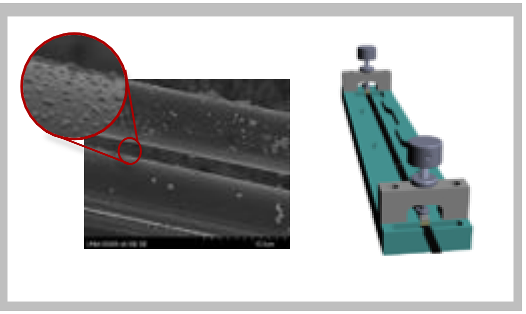

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Nanofillers for Improved Flywheel Materials

September 18, 2014

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U.S. DEPARTMENT OF ENERGY

NNSA

Project: Improved Flywheel Materials

Problem: Flywheels used to level the AC grid need to spin faster, which requires stronger rims. Focused on the material (C-fiber, glass fiber, resin) properties of composite flywheels.

No major changes to basic design, processing parameters, and/or cost can be incurred.

Goal: improve the overall strength of composite flywheel materials, so they can spin faster.

Approach: explore utility of nanomaterials in strengthening composite flywheel rims to improve performance. Low load levels (>5%) of nanoparticle fillers have led to dramatic property changes.

Energy is stored in the rotor as kinetic energy, or more specifically, rotational energy:

$$E_k = \tfrac{1}{2} \bullet I \bullet \omega^2$$

ω = angular velocity, I = moment of inertia of the mass about the center of rotation

The amount of energy that can be stored is dependent on:

$$s_t = \rho \cdot r^2 \cdot \omega^2$$

s_t = tensile stress on the rim, ρ = density, r is the radius, ω is the angular velocity of the cylinder.

Energy Storage Impact: The economics of flywheel-based energy storage can potentially be improved by a factor of 3 or more. The increased storage/supply is necessary to meet expected future complications expected as alternative energies (i.e., solar, wind, etc.) are introduced.

Nanofillers used to improve the composite flywheel materials' properties.

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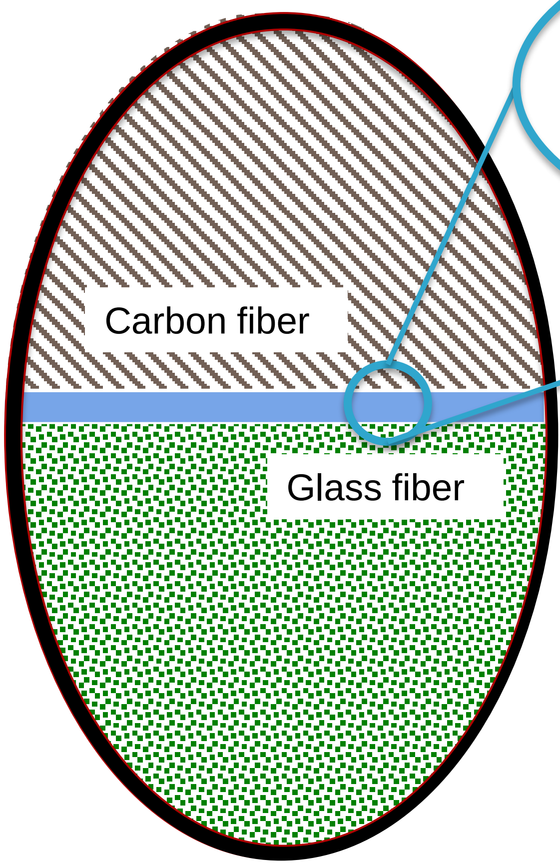
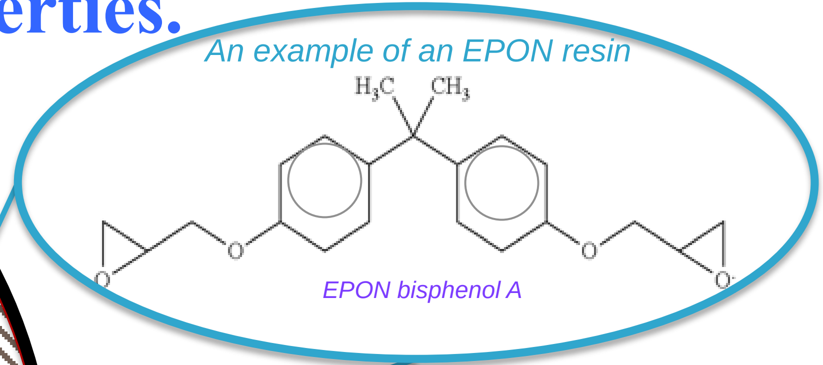
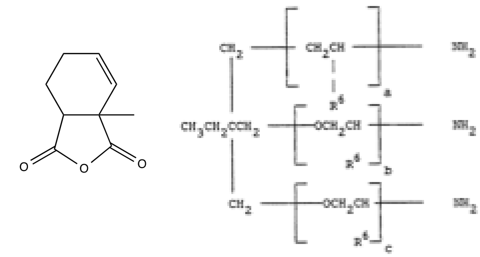


An example of an EPON resin



EPON bisphenol A

LS81k Poly(oxyporpylene) triamine



An activator or crosslinker required to polymerize

Ceramic and Graphene Nanofillers

+ Fillers are a simple cost-effective method to alter resin properties.
+ Meso-sized fillers require high loads (> 60%) due to small surface area.
+ Nanomaterials are 2 D fillers with all surface area; added at low levels.
+ Surface functionality of the nanofiller can interact with the reactive epoxide group of resin.
+ Reactivity can be tailored by surfactant on the nanomaterial
+ Previous results indicate that wires and planes have biggest impact at lowest load level.

Loading (wt %):	4	$Al_2Si_2O_5(OH)_4$:	23%	*storage, 113% flexural strength,*
	3	Al_2O_3:	75%	*tensile strength,*
	2	SiO_2:	3%	*hardness, 57% impact, 65 % flex, 88 % tensile strength,*
	2	ZrP:	52%	*Youngs Modulus, 14% tensile strength 6 %, fracture toughness,*
	0.4% CNT-2%	ZrP:	41%	*Youngs Modulus, 55% tensile strength.*

Nanofiller sample preparation: Carleton vs KCP

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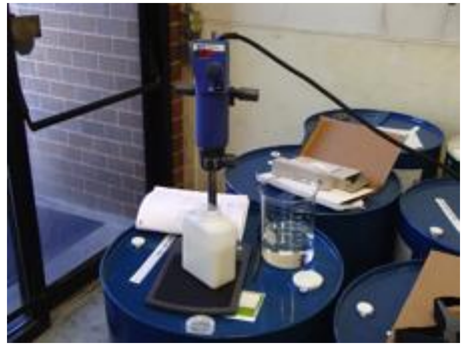
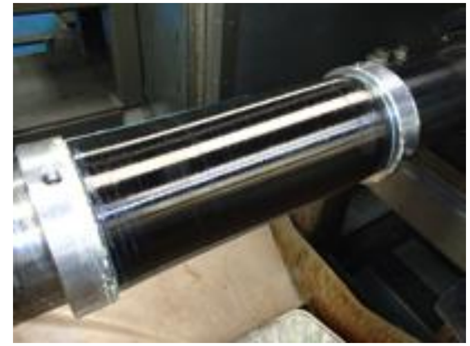
Carleton/Cobham: TiO_2

Part Manufacture:
- Single Tow, near hoop wound

Part Dimensions:
- 4.0 I.D. X .25” thick (4.5 O.D.) X 10” long
- Target 60% Fiber Mass Fraction
- Tubes produced with (5%) TiO_2, and (5%) CNT.





CF/Resin(GNF) Part Manufacture:
- Parts were fabricated at the Cobham/Carleton plant in Westminster, MD.
- Filament winding took place on a Entecwinder.
- Parts were wound onto a 4” diameter, 0.25” thick wall that was 12” long.
- Parts were cured at 100 ^{o}C for 24h, with 5 rpm rotation to prevent flow of resin during cure
- Mandrel was wound at 22 rpm with 6-6.5 Lbs of line tension at the part, single tow, hoop winding.
- Mandrel was cryogenically shrunk after being removed from oven, allowing part to easily slide off.

KCP: Graphene

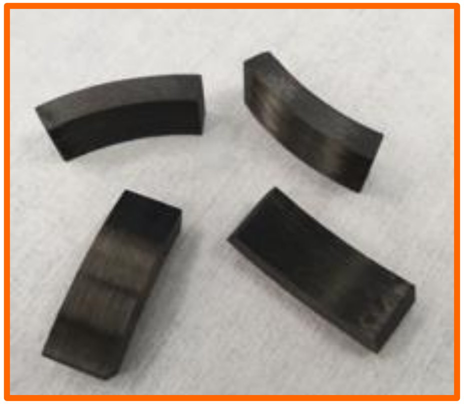
Part Manufacture:
- 4 Simultaneous Tow, no change in angle (resulting in overlap of 3 tow)
- Part Dimensions:
  4’ long, 4” ID, ~ ¼” (6.35 mm),
  78% Fiber Mass Fraction

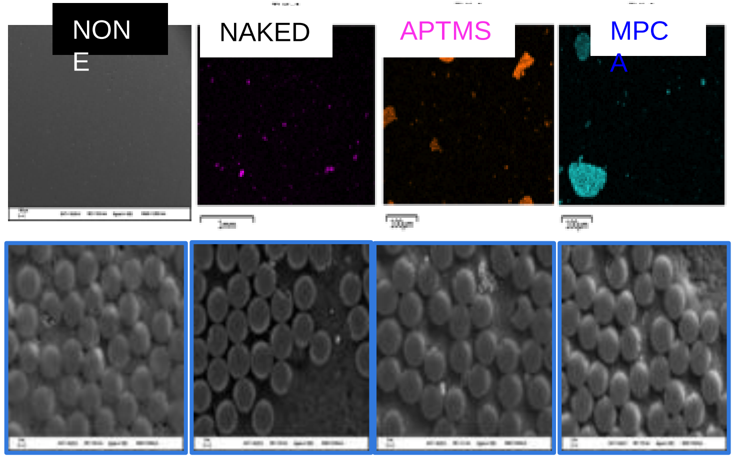
Prepared 0%, 1% and 3% GNF Parts

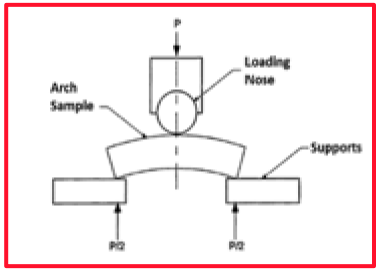
CF/Resin(GNF) Part Manufacture:
- Parts were fabricated in the Mechanical Fabrication and Support Area in the National Secure Manufacturing Center at the Kansas City Plant.
- Filament winding took place on a 6-Axis McClean-Anderson winder.
- Parts were oven cured on a rotating cart for 24 hours at 158 ° F.
- Mandrel designed/fabricated to spec
- Mandrel was cryogenically shrunk after being removed from oven, allowing part to easily slide off.

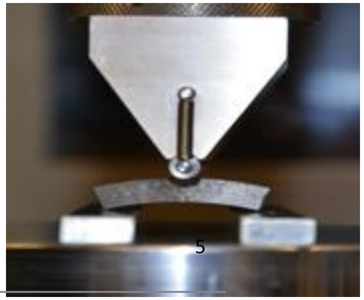
Flywheel: 3-point bend test results show marked improvement in strength

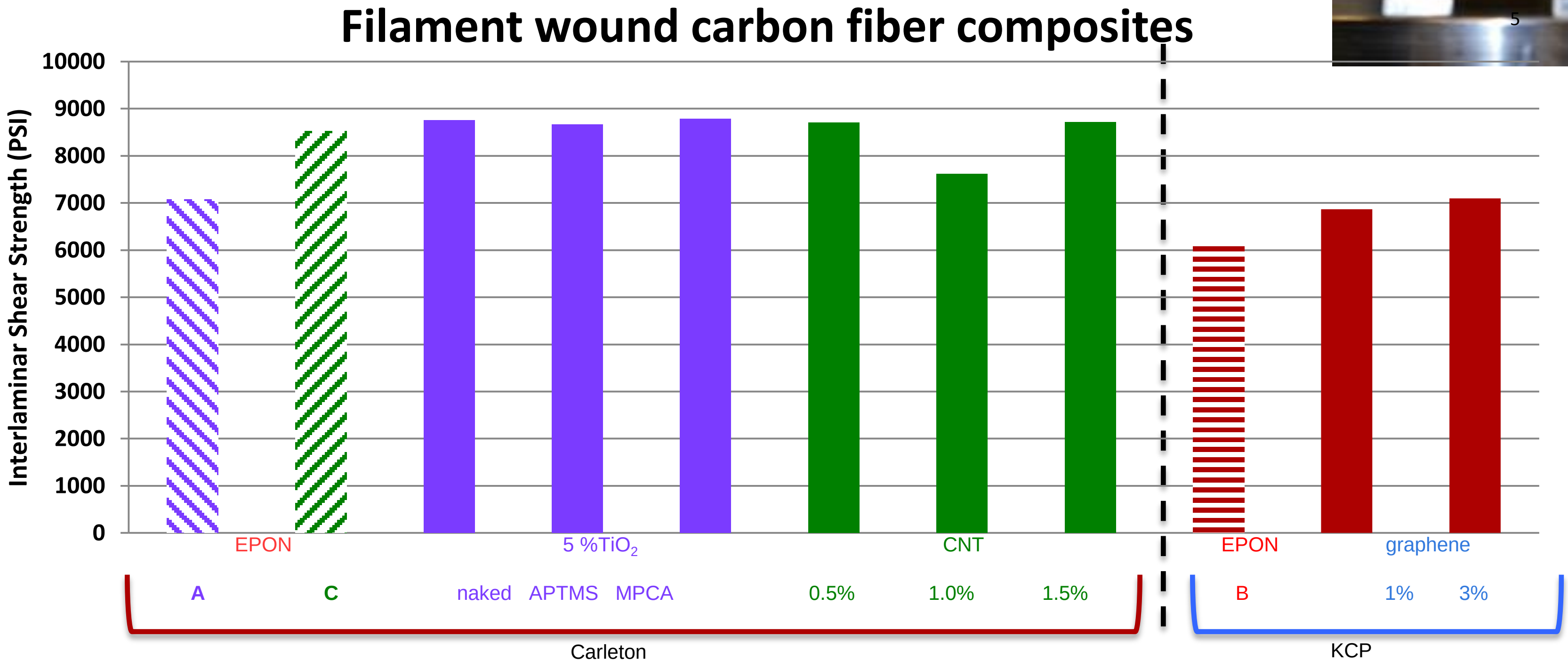
Test samples











Overall Objectives: defining functionalized nanoparticle fillers effects on the 'state-of-the-art' working Flywheel system.

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Team determined approach and tasks assigned based on expertise

- Composite System
- Resin/Epoxy System
- Ceramic Nanomaterials
- Surface Characterization

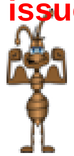
TiO_2 /graphene ceramic nanomaterials

Optimized Functionalized Nanofiller /Epoxy Characterization

Sample Production Evaluation

Test Specimen Functionalized Nanofiller Characterization

+ Increasing transverse strength is the pressing issue.



**** Incorporation of suggested nanomaterials or resins will represent verification of our approach***

Technical Advance Filed

FY14 Flywheel

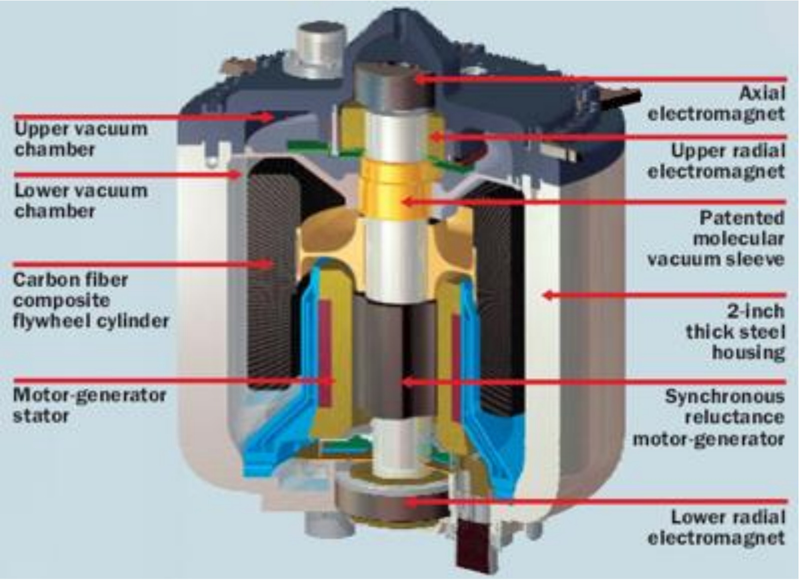
PowerThru formed in 2010 from Pentadyne Power Corporation Beaver Aerospace and Defense.

POWERTHRU
Clean Flywheel Energy Storage

POWERTHRU designs and manufactures advanced flywheel energy storage systems that provide ride-through power and voltage stabilization for power quality and power recycling applications. Designed to provide high-power output and energy storage in a compact, self-contained package.

POWERTHRU flywheel products are a long-lasting, low-maintenance, lightweight, and environmentally-sound alternative to flooded and valve regulated lead-acid (VRLA) batteries in uninterruptible power supply (UPS) systems. POWERTHRU products are developed for commercial application and not home use.

POWERTHRU shipped its first commercial production flywheel in 2004, and continues to provide award-winning flywheel products to critical applications around the world. Flywheels are built in Michigan (seismic Zone 4 rated).



12” diameter; 7.6” tall.

Benefits to all involved are anticipated for the Carleton/Cobham, PowerThru, Sandia, and OE Collaboration.

** 3-way NDA in place**

Carleton/Cobham
- New tech developed - nanofillers
- New customer base

PowerThru
- Comparative analysis of flywheel produced using diff. resin system
- Improved flywheels/same processing
- US based rim provider

Sandia
- Lab scale idea implemented
- TRL 1 to ~7
- Another happy customer

OE
- Increased elect. storage for grid
- Tech Transfer
- US jobs – TiO_2 production

If nano-loaded flywheels provide improved performance:

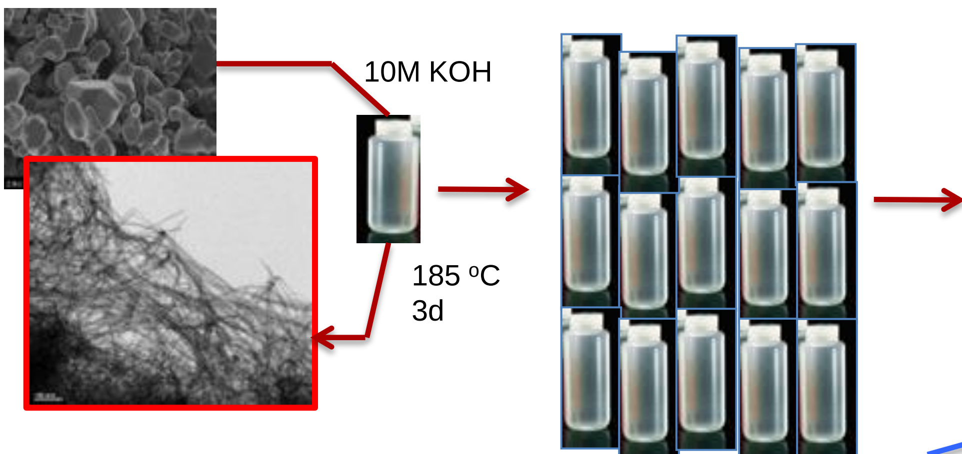
- C/C will have developed a new capability outside of their current manufacturing scope
- New job potential as C/C may assume overseas manufacturing of flywheels; incorporation of nano-wires into an existing composite product can provide an overreaching effect for other technologies/
- Product viability provides stepping stone for incorporation into larger grid-based flywheel systems.
- PowerThru will have the ability to improve their commercial and defense related UPS product

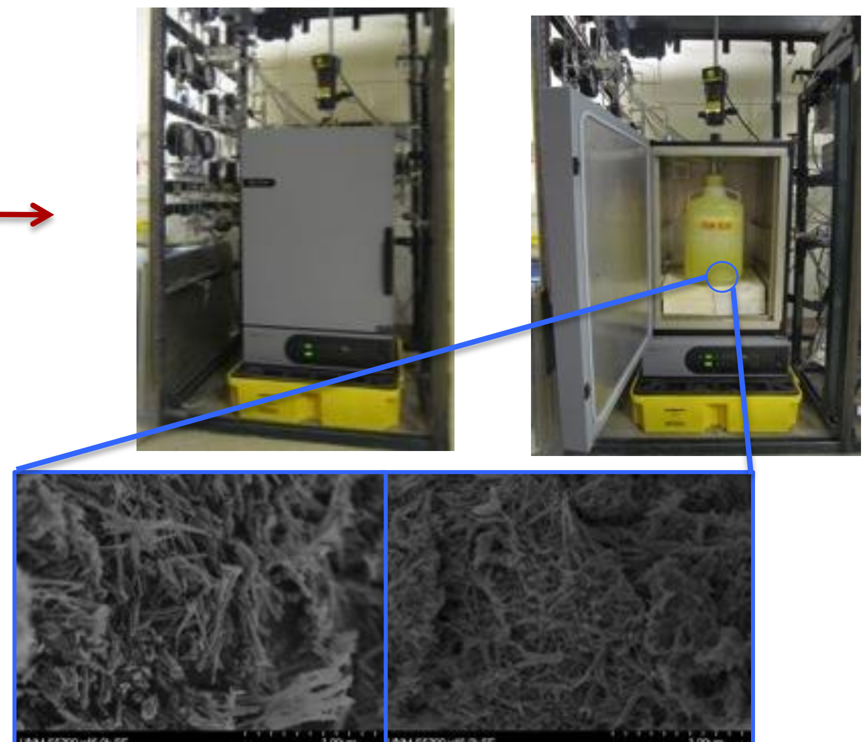
SNL will supply the various nanofillers

- Blank (2) to PowerThru specifications
- **TiO_2 Nanofiller**
- **Graphene sheet filler**
- Al_2O_3 Nanosheet filler

• Sandia will synthesize the **TiO_2** nanowires: requires substantial large scale redesign
5 g (2011) → 500 g (2013) → 5000 g (2014)

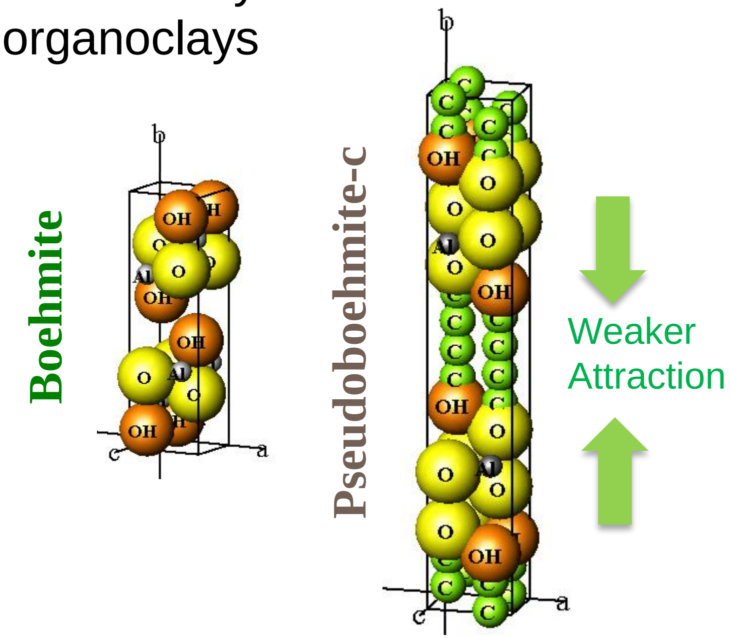
Sandia will prepare or procure graphene materials from commercial sources





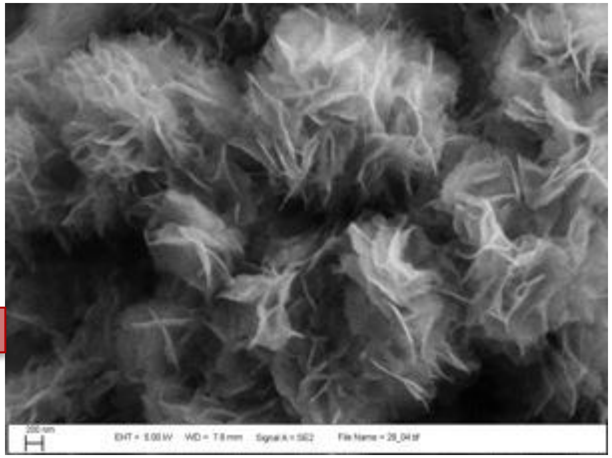
Additional nanofiller that compares planes versus wires being developed.

Glycothermal routes for chemical synthesis lead to organically modified layer materials - organoclays



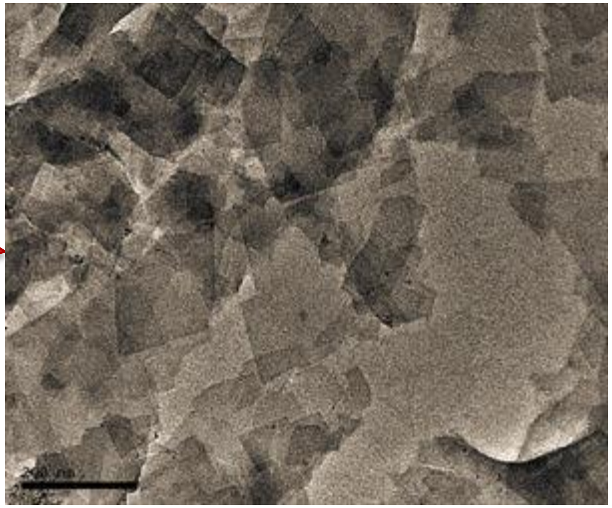
The organoclay has weaker forces bonding layers together, and can be exfoliated into nanosheets of aluminum oxide.

Aggregated Product
Post-Synthesis in 1,4-butanediol



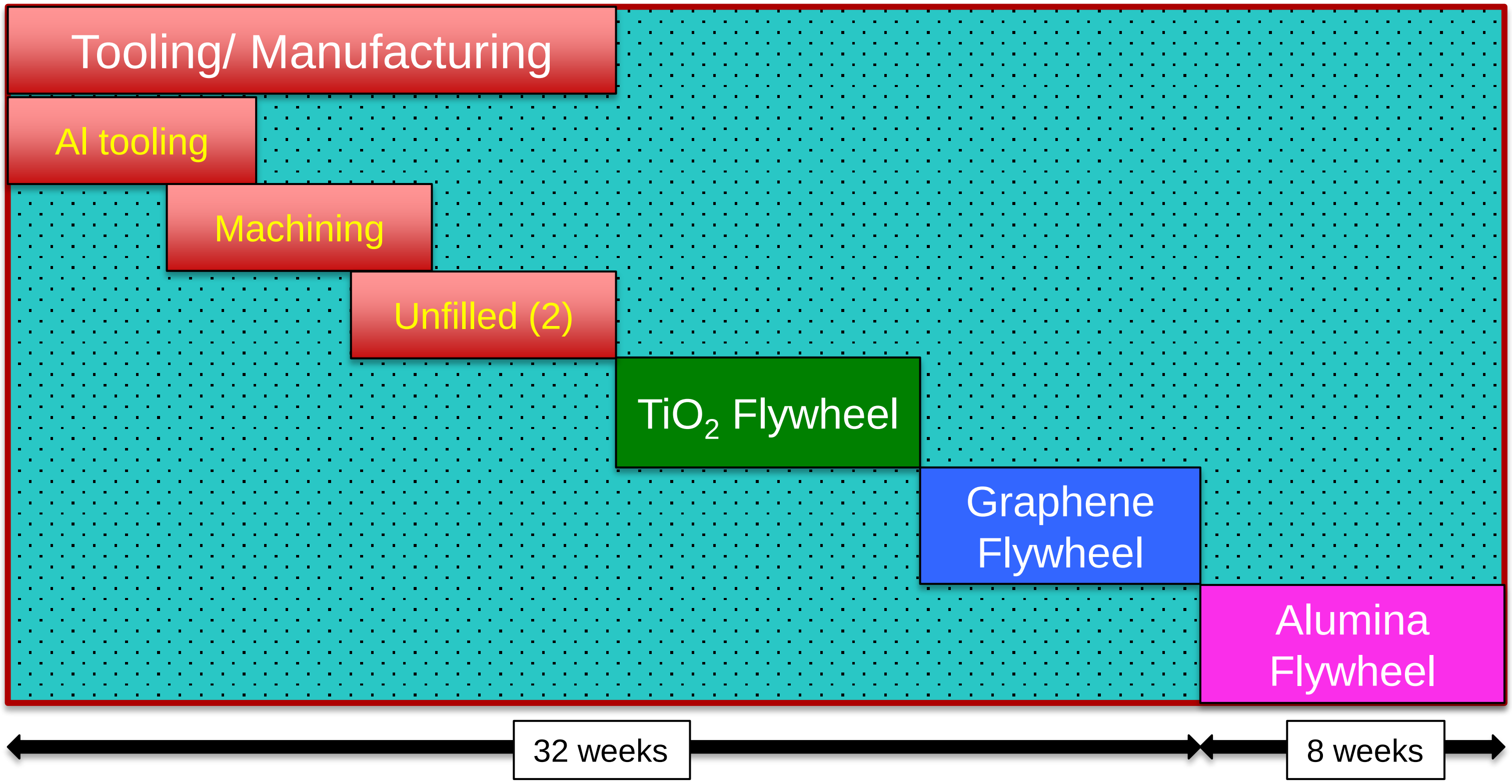
Ethanol, sonication

Exfoliated Material



Technical Advance filed (08/14)

Timeline for flywheel production determined and production initiated.



16 weeks to produce the first unfilled flywheel (includes)

- Manufacturing aluminum tooling to wind rim parts
- Time for machining filament wound rim parts
- Manufacturing time for aluminum tooling to press hub into rim

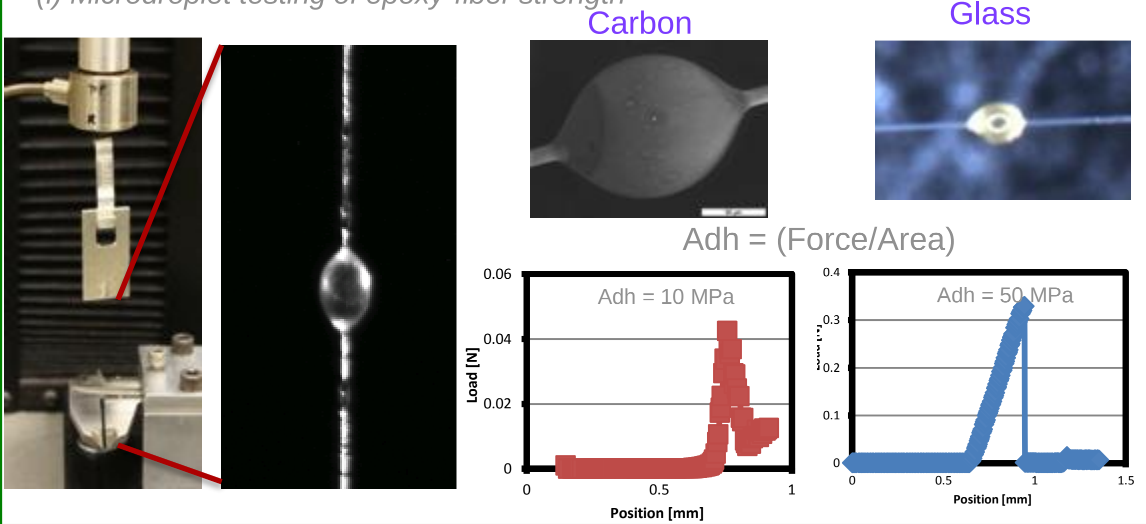
8 weeks to produce the TiO_2 filled flywheel (all processes)

8 weeks to produce each Graphene flywheel (all processes)

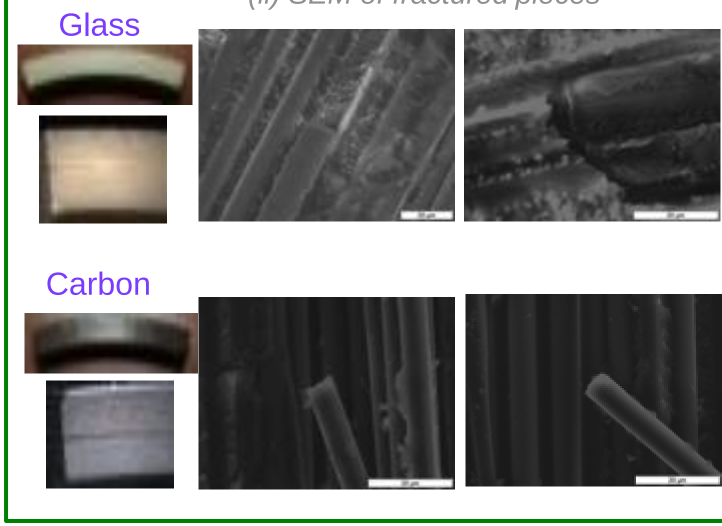
8 weeks to produce the AlO_x filled flywheel (all processes)

C-fiber resin interaction needs to be improved. Functionalization of the C-fiber is underway:

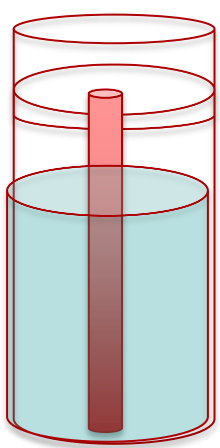
(i) Microdroplet testing of epoxy-fiber strength



(ii) SEM of fractured pieces

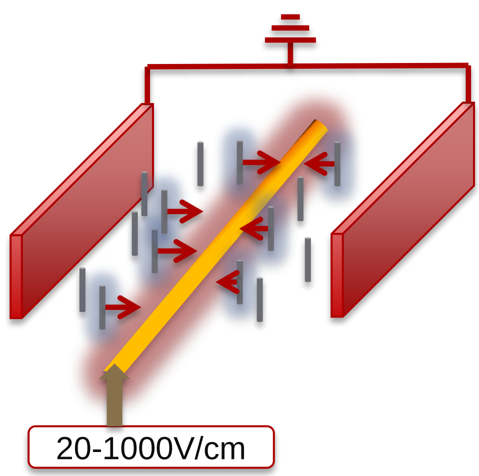


__Solution Growth__ the C-fiber is being treated in different concentrations of metalorganic salts. The changes will be monitored by SEM and attempts to grow ZnO on the carbon will be investigated.

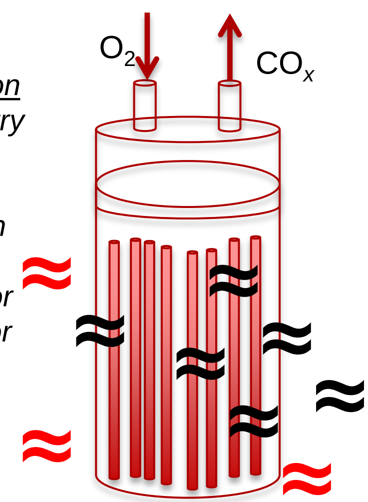


__Electrophoretic Deposition__: Under applied DC voltage, oppositely charged particles are attracted to the C fiber and deposited.

- Scalable, conformal process.
- dependent on surface charge

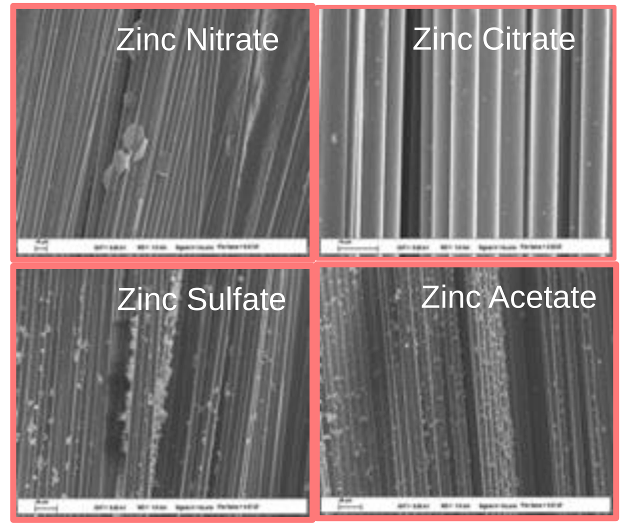


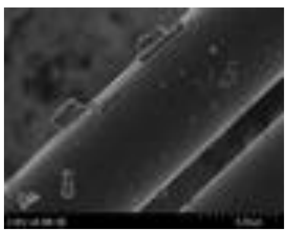
__Thermal oxidation__ reactive chemistry to induce C=O, O-C=O, C-O functionalities on the surface, that could be used for further grafting or better adhesion with the polar matrix.



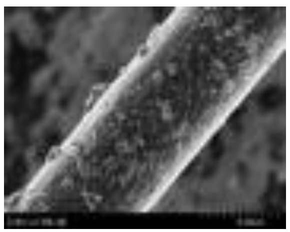
Surfaces can be modified using commercially viable routes. Dog-bone testing initiated.

120°C, 3 days

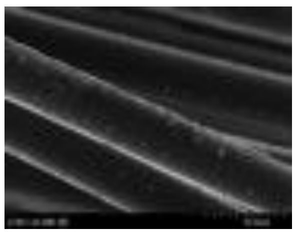




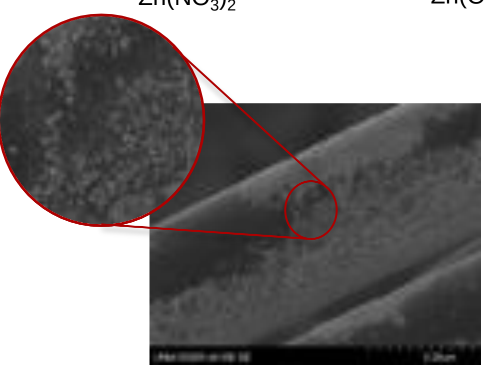
$Zn(NO_3)_2$

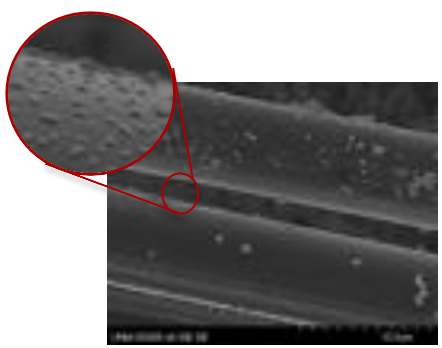


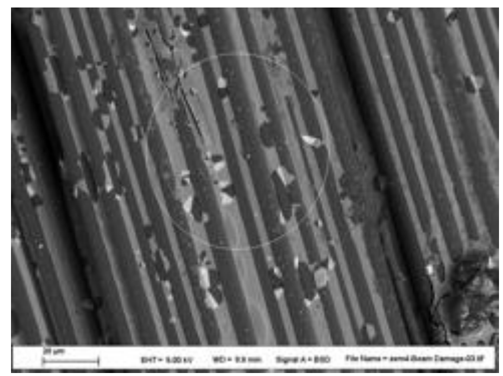
$Zn(OAc)_2$



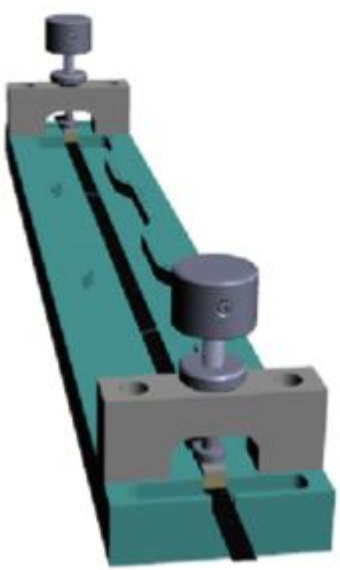
$Zn(OAc)_2$







Cut away of dog-bone mold with Carbon Fiber Tow under tension.



CF-Resin Interaction testing with acoustic emission (Miller - MSU)

Summary/Conclusions

FY14 Overall

• v. Large scale samples successfully prepared using new: method, setup, workspace, and ES&H concerns addressed.

• Ceramic nanosheet developed for filler – pseudo-boehmite

• 3-way contract in place for analyzing nano filler functionalized flywheels.
  (a) 3-way NDA successfully executed
  (b) contract for flywheel components
    i. Unfilled (blanks (2)) to PowerThru specifications
    ii. TiO_2 nanofiber fillers
    iii. Graphene nanosheet filler
    iv. Al_2O_3 nanosheet fillers

• Functionalized C-fiber synthesized, placed in a dog-bone resin setup, and submitted for testing.
    i. Contract with Montana State University (Miller)
    ii. Dog-bone cast developed
    iii. C-fiber centered/tensioned in cast.

Future Tasks: Milestones for FY15

• Test breakdown properties of operating flywheels
  + contract with PowerThru
  + transfer of flywheels.
  + testing of breakdown properties.

• Analysis of results and determine if optimization of nanofillers to improve overall spin speed/energy storage/AC grid stabilization.

• Formulation of TiO_2 dispersion and optimized Graphene

• Economic impact evaluation.

• Analyze results of C-fiber resin interaction using dog-bone test and optimize:
  (i) baseline (blank),
  (ii) solution ceramic, and
  (iii) organic
  (iv) mixture (ii/iii)

• Method for large scale C-fiber modification developed

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Energy Storage Program Manager – Dr. Imre Gyuk

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